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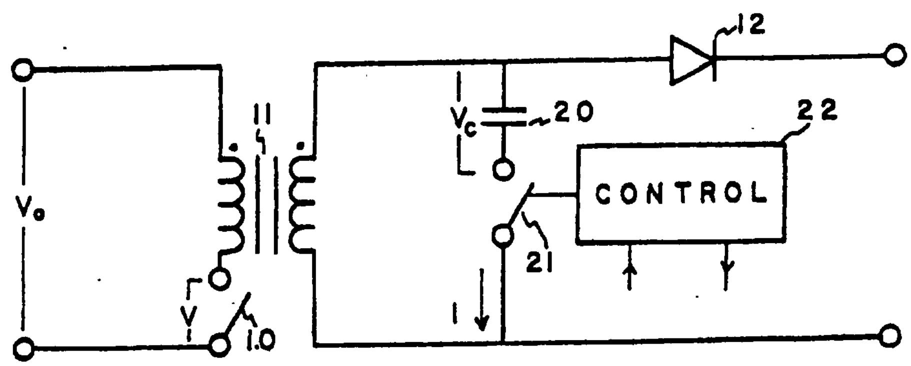
(54) Title: OPTIMAL RESETTING OF THE TRANSFORMER'S CORE IN SINGLE ENDED FORWARD CONVERTERS



(57) Abstract

The transformer's core (11) in single ended forward converters is reset by a 'magnetizing current mirror' consistin of a capacitor (20) in series with an auxiliary switch (21) which, during the OFF period of the primary switch (10), couple the capacitor (20) to one of the transformer's windings to form a resonant circuit with the transformer's magnetizing inductance. The resonant circuit recycles the transformer's magnetizing energy by creating a mirror image of the magneti flux between ON periods. This maximizes the flux swing available within a given core. The voltage stress on the primar switch (10) is minimized as the voltage across the switch (10) during the OFF period is approximately constant and autc matically tailored to avoid dead time for arbitrary values of the switch duty cycle.

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OPTIMAL RESETTING OF THE TRANSFORMER'S CORE IN SINGLE ENDED FORWARD CONVERTERS

Background of the Invention

Field of the Invention

This invention relates to DC-to-DC converters which process electrical power from a source, at an input DC voltage, to deliver it to a load, at an output DC voltage, by selectively connecting a power transformer to the source and the load via solid state switches. In particular, the invention relates to converters of the forward type, in which the power transformer is simultaneously connected to the source and the load. More particularly, the invention relates to forward converters of the single ended type, in which the power flow from source to load is controlled by a single solid state switch.

Description of the Prior Art

This invention relates to the class of DC-to-DC converters which incorporate the topology represented in Figure 1. A converter in that class is referred to as a "single ended forward" converter because power flow is gated by a single switch 10 and energy is transferred forward, from the primary winding to the secondary winding of the transformer 11, during the ON period of the switch 10.

Converters in this class present a unique problem, in that the conversion topology does not inherently define the mechanism by which the transformer's core is to be reset during the OFF period of the switch. The solution to this problem

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is not unique, as evidenced by the multiplicity of proposals found in the literature which, in order to implement the reset function, complement the topology represented in Figure 1 by differing choices of auxiliary circuitry. The differences are important since they affect the cost of the converter, as well as its efficiency and power density.

The traditional approach, represented in Figure 2a, has been to reset the core via an auxiliary transformer winding connected with inverted polarity in series with rectifier 13. The operation of this reset mechanism is illustrated in Figure 2b, where, in addition to idealized component behavior, a one-to-one turn ratio between auxiliary and primary windings has been assumed. This Figure exemplifies a sequence of two ON periods, separated by an OFF period, to enable the core to reset itself. The Figure displays, as functions of time, the state of the switch 10, the voltage V across the switch, and the current I through the auxiliary winding.

The first ON period is given by the time interval between t_1 and t_2. During this interval, the voltage V across the switch 10 vanishes and the source voltage V_o is impressed upon the primary winding. The magnetizing inductance controls the slope of the magnetizing current, flowing in the primary winding, and of the magnetizing energy which accumulates in the transformer's core. The current I vanishes, as the rectifier 13 is reverse biased, in a blocking

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state, and thus keeps the auxiliary winding inoperative.

At time t_2, the opening of the switch 10 interrupts current flow in the primary winding. Neglecting the effects of leakage inductance between primary and auxiliary windings, the voltage V is clamped to $2V_o$ as the rectifier 13 becomes forward biased and begins to conduct the magnetizing current. The current I through the auxiliary winding is then equal to the peak value I_p of the magnetizing current. Following time t_2, I decays as magnetizing energy is returned to the voltage source V_o. At time t_3, the recycling of the magnetizing energy is completed, the current I vanishes, and, neglecting hysteresis, the magnetic flux through the transformer's core is reset to zero. The time interval between t_2 and t_3 is the core reset period. Having assumed a one-to-one primary to auxiliary turn ratio, this period equals the ON period t_2-t_1.

The remainder of the cycle, between times t_3 and t_4, is the "dead" period. In this period, the switch 10 remains open, the voltage V across it equals the source voltage V_0, and the current I vanishes. The circuit in Figure 2a is not efficiently functional during dead time.

The relative duration of the dead period depends upon the duty cycle of the switch 10 (assumed to be 33% in Figure 2b). At 50% duty cycle, the dead period vanishes. Operation beyond 50% duty cycle would lead to saturation of the transformer's core and (catastrophic) converter failure.

Thus, the traditional reset mechanism, represented in Figure 2a, presents an inherent limitation in the available duty cycle range. This is a significant drawback as it impairs the ability of the converter to regulate against wide variations in the source voltage or in the load. Another drawback of the traditional reset method is that allowed values of the duty cycle are in general associated with a non-vanishing dead time. The existence of a dead time causes the switch 10 to experience a peak voltage greater than is in principle necessary to reset the core in the time interval between ON periods.

Similar limitations apply, to a varying degree, to any other reset mechanism which involves a variable dead time to accomodate variations in the switch duty cycle. Reset methods falling into this category are found in S. Hayes, Proceedings of Powercon 8, Power Concepts Inc. 1981 and in R. Severns, ibid..

To avoid these limitations, a different approach to the resetting of the transformer's core in single ended forward converters was proposed by S. Clemente, B. Pelly and R. Ruttonsha in "A Universal 100 KHz Power Supply Using a Single HEXFET", International Rectifier Corporation Applications Note AN-939, December 1980. These authors suggest a capacitor-resistor-diode network, as represented in Figure 3a. The network clamps the switch to the minimal peak voltage consistent with a given source voltage and switch duty cycle, eliminating the need for dead time while allowing

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for a wide range of duty cycles. Attainment of these design goals is actually dependent upon component characteristics and values. In particular, the resistor 15 must be sized small enough so that the transformer's magnetizing current does not ever vanish.

With this assumption, the operation of this reset circuit is illustrated in Figure 3b. As in the example given to illustrate the traditional reset mechanism, a sequence of two ON periods separated by an OFF period, with a 33% duty cycle is considered. The figure displays, as functions of time, idealized waveforms defining the state of the switch 10, the voltage V across it, and the current I through the rectifier 13. During the OFF period, the latter coincides with the transformer's magnetizing current.

As exhibited in Figure 3b, the voltage V across the switch 10 is now a rectangular waveform with a peak value equal to $1.5V_o$. The current I through the rectifier 13 is a trapezoidal waveform which, during the OFF period, decays from a peak value (I_p+I_o) to a minimum value I_o, a non-negative function of V_o and the duty cycle D.

A comparison of the voltage waveform of Figure 3b with the corresponding one in Figure 3b emphasizes the main advantage of the capacitor-resistor-diode clamp: a reduction in the voltage stress applied to the switch 10. A related advantage is the elimination of bounds resulting from core saturation on the duty cycle range, enabling the converter to remain functional over

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wider ranges of input voltage and output load. A further advantage is the avoidance of auxiliary transformer windings which simplifies transformer construction. Unfortunately, while attaining these benefits, the reset mechanism of Figure 3a compromises the converter's efficiency and power density.

The reduction in the efficiency of the conversion process arises principally from the dissipation of magnetizing energy accumulated in the transformer during the ON period. Instead of being recycled, this energy is converted into heat by the clamp circuit. This power waste is significant, particularly in an otherwise efficiency mindful conversion system.

The reduction in power density results mainly from an increase in the size of the transformer which is rendered necessary by a decrease in the available dynamic flux swing for the magnetic material making up the transformer's core. This is evidenced in Figure 3b by the quantity referred to as I_o, which represents a non-negative, static component of the magnetization current. The component shifts the peak value of the magnetizing current, leading to an excitation of the transformer's core which brings the magnetic material closer to saturation. The consequent decrease in available flux swing reduces the power handling capability per unit volume at solid state switch (distinguished from the primary switch which controls the converter's power flow), and of a switch control circuit. The switch control circuit

operates the auxiliary switch in its open state during the converter's ON period, when the primary switch is closed, and in its closed state during the converter's OFF period when the primary switch is open. The auxiliary switch (operated by such a control circuit) and storage capacitor are connected in parallel with a transformer winding.

The apparatus defined above resets the transformer's core by implementing the conceptual function of a "magnetizing current mirror": it takes the magnetization at the end of the ON period and creates a mirror image of it prior to the initiation of the following conversion cycle. The image is created via the charging and discharging of the storage capacitor which forms a resonant circuit with the transformer's magnetizing inductance. The capacitor is sized so that the period of this resonant circuit is considerably greater than the conversion period. Consequently, the capacitor's voltage and the voltage across the primary switch are approximately constant during the OFF period.

The new apparatus provides optimal resetting of the transformer's core in single ended forward converter topologies:

it is non-dissipative, as it recycles the core's magnetization energy via intermediate storage in a resonant circuit;

it maximizes the available flux swing, as it creates a mirror image of the magnetic flux between ON periods;

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it minimizes the voltage stress on the (primary) switch, as it applies to this switch during the OFF period an approximately constant voltage which is automatically tailored to avoid dead time;

it does not introduce constraints on the switch duty cycle due to core saturation;

it simplifies transformer construction, as it can be implemented without auxiliary windings.

Brief Description of the Drawings

Figure 1 defines the general class of single ended forward converters.

Figure 2a shows the auxiliary transformer winding which has been traditionally employed to reset the core in single ended forward converters.

Figure 2b exemplifies the operation of the reset mechanism in Figure 2a by displaying a possible time sequence of states for the switch 10 and the corresponding idealized waveforms for the voltage V, across the switch 10, and the current I, in the auxiliary transformer winding.

Figure 3a shows a capacitor-resistor-diode network which has been employed in the prior art as an alternative mechanism for resetting the core in single ended forward converters.

Figure 3b provides an example of the operation of the reset mechanism in Figure 3a analagous to that of Figure 2b to allow for a direct comparison of voltage and current waveforms.

Figure 4a discloses a preferred embodiment of the new reset mechanism for single ended forward converters, consisting of a "magnetizing current

mirror" connected across the transformer's secondary.

Figure 4b discloses voltage and current waveforms useful in describing the operation of the new reset mechanism.

Figure 4c discloses a preferred implementation of the magnetizing current mirror in which the auxiliary switch is realized in terms of a MOSFET transistor and its integral reverse rectifier.

Figure 4d discloses equivalent circuit diagrams characterizing the ON and OFF periods of a single ended forward converter reset by a magnetizing current mirror.

Figure 4e discloses an embodiment of the new reset mechanism in which the magnetizing current mirror is connected across the transformer's primary.

Figure 4f discloses yet another embodiment of the invention in which the magnetizing current mirror is connected across an auxiliary transformer winding.

Figure 5 compares idealized waveforms exemplifying the time evolution of the magnetic flux across the transformer's core in a single ended forward converter reset by: a) the traditional mechanism, employing an auxiliary transformer winding; b) the capacitor-resistor-diode network; c) the optimal reset mechanism, utilizing a magnetizing current mirror.

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Detailed Description of the Invention

Referring now to Figure 4a, the primary switch 10 selectively couples the primary winding of transformer 11 to a source of voltage V_o. A rectifier 12 is connected in series with the secondary winding of transformer 11 and is oriented to conduct a current during the ON period of the primary switch 10. These are conventional elements of a single ended forward converter. In order to reset the transformer 11 during the OFF period of the primary switch 10, these elements are complemented by a "magnetizing current mirror".

The magnetizing current mirror comprises the storage capacitor 20, the auxiliary switch 21 and the switch control circuit 22. The capacitor 20 and the switch 21 are connected in series. The switch 21 is operated by the control circuit 22 in accordance with a control logic requiring that the auxiliary switch 21 be opened prior to the ON period of the primary switch 10, and closed after this period. To accomplish this function, as suggested by the arrows at the bottom of the box representing the switch control circuit 22, this circuit is interfaced with primary switch control circuitry, not represented in the figure. The implementation of the control circuit and of its interface can be realized in a number of ways which will become obvious to those skilled in the art.

In Figure 4a, the magnetizing current mirror is connected in parallel with the secondary winding of transformer 11. Assuming an equal number of turns between this and the primary

winding, and neglecting the effects of leakage inductance between primary and secondary windings, and parasitic effects including the ones associated with winding capacitance or the capacitance of non-ideal hardware realizations of the primary switch 10 and auxiliary switch 21, the operation of the magnetizing current mirror as a reset mechanism is illustrated by an example in Figure 4b.

As in the examples of Figure 1b and 2b which were used to characterize the operation of reset mechanisms found in the prior art, Figure 4b considers a sequence of two ON periods separated by an OFF period, with a 33% duty cycle. The figure displays, as functions of time, idealized waveforms defining the state of the switch 10, the voltage V across it and the current I through the auxiliary switch 21.

At time t_1, the auxiliary switch 21 is opened and the primary switch 10 is closed, initiating the first ON period. During this period, the voltage V across the primary switch and the current I through the auxiliary switch vanish. The source voltage V_o is impressed upon the primary winding of transformer 11, causing the magnetic flux ϕ across the transformer's core to change with time as indicated by Faraday's law. If N is the number of primary (and secondary) turns, the total change in the flux ϕ is $V_o(t_2-t_1)/N$. Concurrent with this is a change in the magnetizing current given, in terms of the magnetizing inductance L_M, by $V_o(t_2-t_1)/L_M$.

At time t_2, the primary switch 10 is opened and the auxiliary switch 21 is closed, initiating the OFF period. During this period, the voltage across the auxiliary switch and the current through the primary switch vanish. The voltage V across the primary switch is clamped to a value $V_p=V_o+V_c$, where V_c is the voltage across the storage capacitor 20. Conduction of the magnetizing current is transferred to the secondary winding where the current loop is closed by the storage capacitor 20 and the auxiliary switch 21. Initially, this current, I, is negative in sign and equal in magnitude to $I_p/2$.

The evolution of the system during the OFF period, the time interval between t_2 and t_4, depends upon the capacitance value C chosen for the storage capacitor 20. C should be chosen to be large enough so that the time dependence of the voltage, V_c, across the capacitor can be approximately neglected. This accounts for the constancy of the voltage V, and the linear rise of the current I, both displayed in Figure 4b. Invoking once again Faraday's law, the total change in the magnetic flux ϕ during the OFF period is then approximately given by $-V_c(t_4-t_2)/N$. By equaling the magnitude of this change to the corresponding flux change during the ON period, it follows that

$$V_p \simeq V_o(1+D) \qquad \text{Eq.(1)}$$

where $D=(t_2-t_1)/(t_4-t_2)$ is the primary switch duty cycle. The total change in the

magnetizing current I during the OFF period is approximately given by $-V_c(t_4-t_2)/L_M$. Since the integral of the magnetizing current I during the OFF period must vanish (under steady state conditions), it follows that

$$I_p/2 \simeq V_o t_{ON}/(2L_M) \quad , \quad \text{Eq.}(2)$$

where $t_{ON}=(t_2-t_1)$ is the ON time of the primary switch.

The evolution of the system during the OFF period may be analyzed further by dividing the period into two intervals, t_2-t_3 and t_3-t_4, of equal duration, characterized respectively by negative and positive values of the magnetizing current I. In the first interval, the magnetizing current charges the storage capacitor 20, and storage of magnetizing energy is progressively transferred from the transformer to the capacitor. This process is completed at time t_3 when the magnetizing current vanishes. In the second interval, the magnetizing current discharges the storage capacitor 20, and storage of magnetizing energy is progressively transferred back from the capacitor to the transformer. This process is completed at time t_4 when a mirror image of the magnetizing current has been formed and magnetizing energy has been reflected into the transformer, resetting it for the next cycle.

Because of the alternating character of the magnetizing current I, the auxiliary switch 20 must be able to conduct negative as well as positive currents, in addition to being able to block positive voltages. This observation suggests MOSFET transistors as natural candidates to implement the functions of the switch 21.

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Figure 4c shows a magnetizing current mirror in which the auxiliary switch 21 is implemented with a MOSFET transistor. The reverse rectifier inherent to the MOSFET is explicitly shown. Thus the auxiliary switch 21 can be thought of as being always closed to negative currents and selectively closed to positive currents. The flow of positive currents is controlled by the switch control circuit 22 which applies a suitable voltage to the gate of the MOSFET.

Referring back to the example of Figure 4b, it is apparent that the MOSFET 21 can be turned on at any time between t_2 and t_3 without disrupting the operation of the magnetizing current mirror. Such a delay does not represent "dead" time since during this time the reset mechanism is operational. On the other hand, a delay between the opening of the auxiliary switch 21 and the closing of the primary switch 10 represents dead time. For this reason it is efficient to keep such a delay to a minimum, consistent with the requirement to avoid an overlap between switches. However, a small delay is useful to allow the magnetizing current to charge and discharge parasitic capacitances associated with the switches and windings.

A different perspective on the operation of the magnetizing current mirror as a reset mechanism for single ended forward converters is offered by Figure 4d showing equivalent circuit diagrams characterizing the converter's ON and OFF itself to a varying duty cycle, the magnetizing

current mirror and the transformer's core define an essentially closed system: magnetizing energy transferred from the transformer to the storage capacitor is injected back into the transformer within the converter's OFF period. This internal recycling is only incomplete to the extent that non-ideal circuit elements give rise to energy losses. These may be accounted for by modifying the resonant circuit of Figure 4d with the addition of resistive components representing the effects of losses associated with the transformer's core, the winding resistance and the equivalent series resistances of the storage capacitor 20 and the auxiliary switch 21.

The equivalent circuits of Figure 4d suggest that applications of the magnetizing current mirror to the resetting of the transformer's core in single ended forward converters need not be restricted to the topology of Figure 4a. Useful variations of the new reset machanism are indeed obtained by connecting the mirror in parallel with different transformer windings.

In Figure 4e, the magnetizing current mirror is connected in parallel with the primary winding of transformer 11. The main advantage of this topology, relative to that of Figure 4a, originates from a direct coupling of the mirror to the primary switch 10. This eliminates a certain amount of ringing of the voltage V across the primary switch, due to leakage inductance and parasitic capacitances, which is present with the

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topology of Figure 4a. However, this is not a serious problem. On the other hand, a MOSFET implementation of the switch 21 in Figure 4e would require the use of a p-channel device and/or a floating gate drive. This is a relatively serious drawback for this topology.

In Figure 4f, the magnetizing current mirror is connected in parallel with an auxiliary transformer winding. Possible advantages to this configuration originate from the flexibility provided by the choice of turn ratio between auxiliary and primary windings, and the possibility to magnetically couple these windings closely. The trade off is added complexity in transformer construction.

These and other possible variations in the detailed implementation of the new reset mechanism share the same equivalent circuits of Figure 4d and the same fundamental advantages when compared to reset mechanisms known in the prior art. Some of these advantages are made more evident by referring to Figure 5, which compares the idealized behavior of the magnetic flux as it would evolve in the examples of Figures 2b, 3b and 4b, corresponding to: a) the traditional reset mechanism; b) the capacitor-resistor-diode network; c) the new reset mechanism. The curves denoted respectively by a, b and c define as a function of time the flux across a core made of soft ferromagnetic material of negligible hysteresis. The saturation flux is denoted by ϕsat.

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Among the three reset mechanisms considered in Figure 5, the capacitor-resistor-diode network (b) is the one that brings the core closest to saturation and does not recycle the core's magnetization energy. This qualifies this reset mechanism as the most inefficient in utilizing space (the volume of the core) and energy. Its redeeming feature is the constancy in the slope of the flux curve between t_2 and t_4 which, in view of Faraday's law, implies minimal voltage stress on the converter's primary switch.

Some of the drawbacks of the traditional reset mechansim (a) stem from the greater slope of the flux curve between t_2 and t_3 and vanishing slope between t_3 and t_4. These observations imply greater voltage stress on the primary switch, the presence of dead time, and a (50%) limitation on the duty cycle. Other drawbacks stem from the asymmetry between positive and negative flux, which signifies inefficient use of the core's volume and increased core energy losses.

In light of these considerations, the nature of curve c, characterizing the new reset mechanism, speaks for itself and suggests that a magnetizing current mirror should provide optimal resetting of the transformer's core in single ended forward converters.

Other embodiments are within the following claims.

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CLAIMS

1. In a single ended forward converter in which energy is transferred from a primary winding to a secondary winding of a transformer during the ON period of a primary switch, circuitry for resetting said transformer during the OFF period of said primary switch, comprising:

a storage capacitor;

an auxiliary switch connected in series with said storage capacitor;

a switch control circuit operating said auxiliary switch in accordance with a control logic such that (a) said auxiliary switch is opened prior to the ON period of said primary switch, (b) said auxiliary switch is closed after the ON period of said primary switch.

2. The transformer resetting apparatus of claim 1 wherein said circuitry is connected in parallel with said secondary winding.

3. The transformer resetting apparatus of claim 1 wherein said circuitry is connected in parallel with said primary winding.

4. The transformer resetting apparatus of claim 1 wherein said transformer further includes an auxiliary winding, wherein said circuitry is connected in parallel with said auxiliary winding.

5. The transformer resetting apparatus of claim 1 wherein said auxiliary switch is a MOSFET transistor with an integral reverse diode.

6. In a single ended forward converter in which energy is transferred across a transformer during the ON period of a primary switch, an apparatus for recycling the magnetizing energy of said transformer during the OFF period of said primary switch, comprising:

a storage capacitor;

auxiliary switching means to selectively couple said storage capacitor to said transformer, wherein said storage capacitor and said transformer form a resonant circuit during the OFF period of said primary switch.

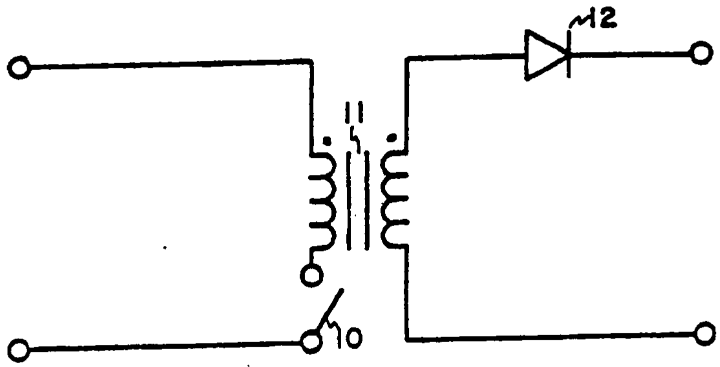

FIG. 1

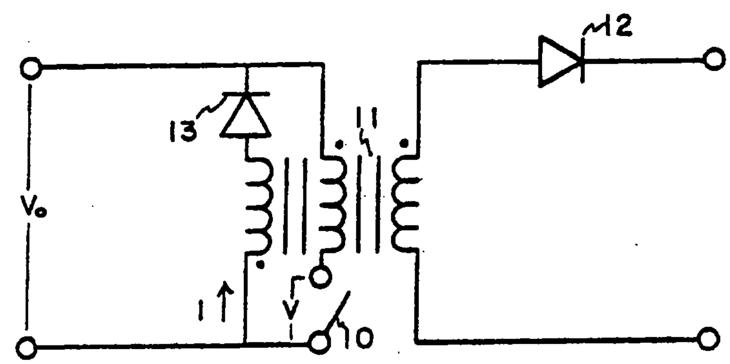

FIG. 2a

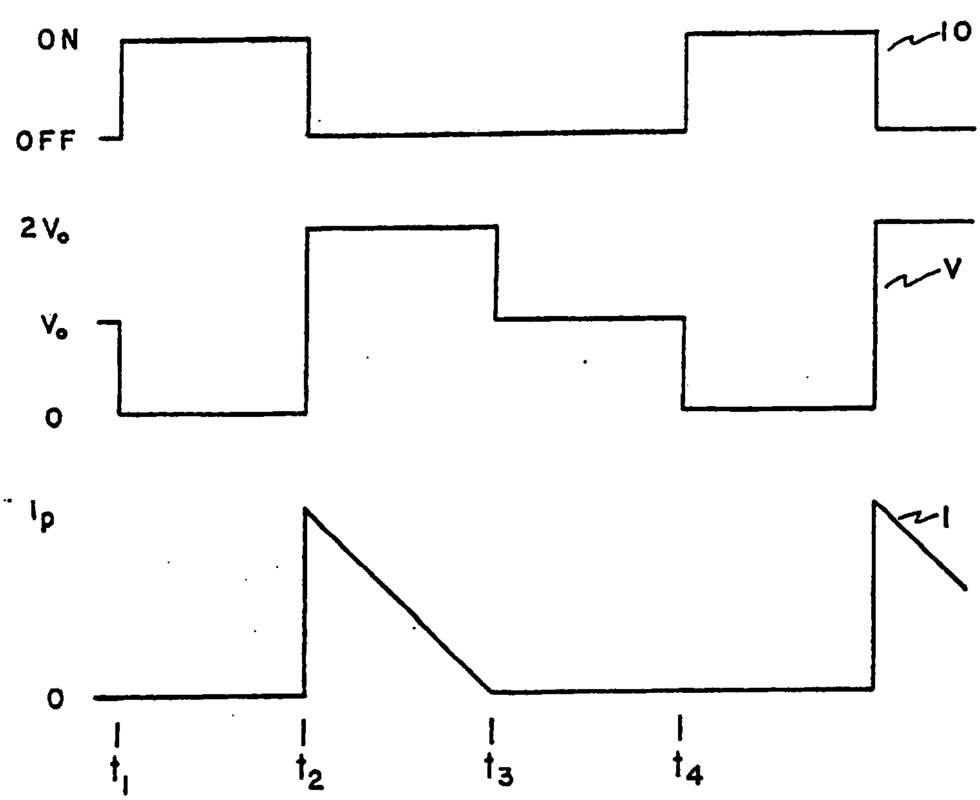

FIG. 2b

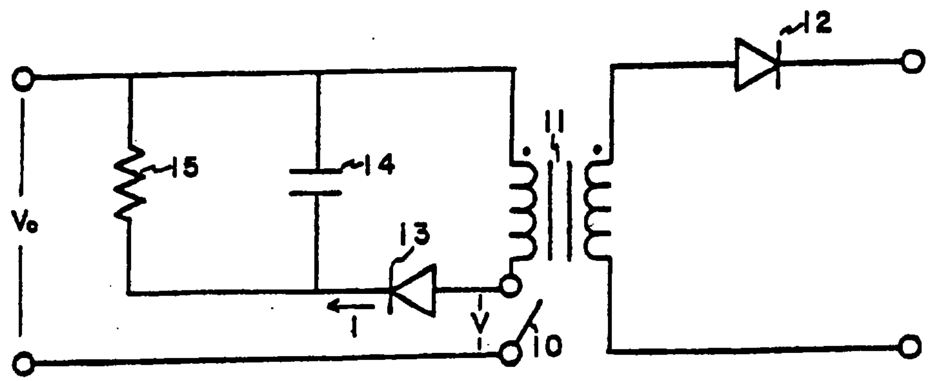

FIG. 3a

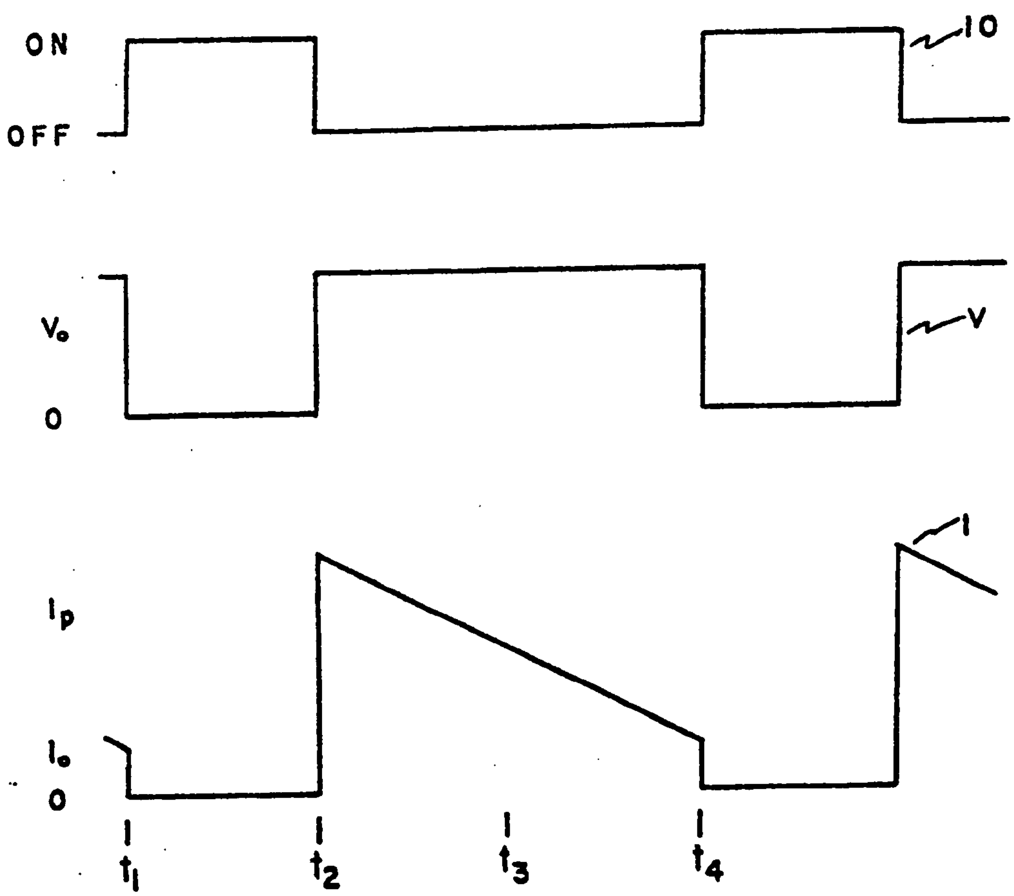

FIG. 3b

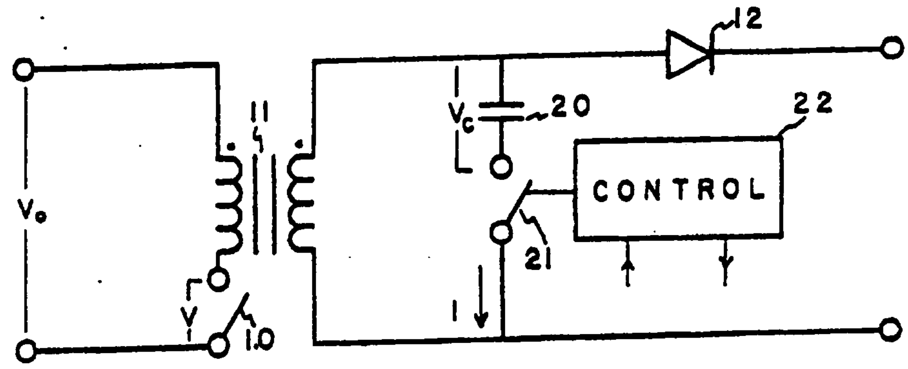

FIG. 4a

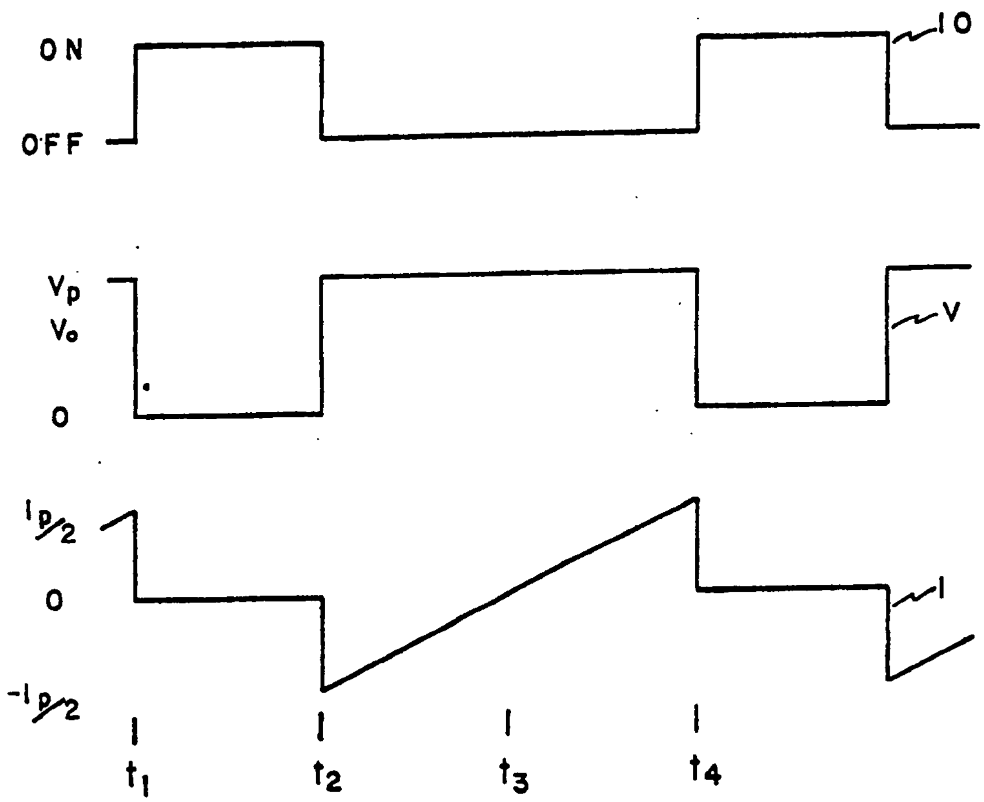

FIG. 4b

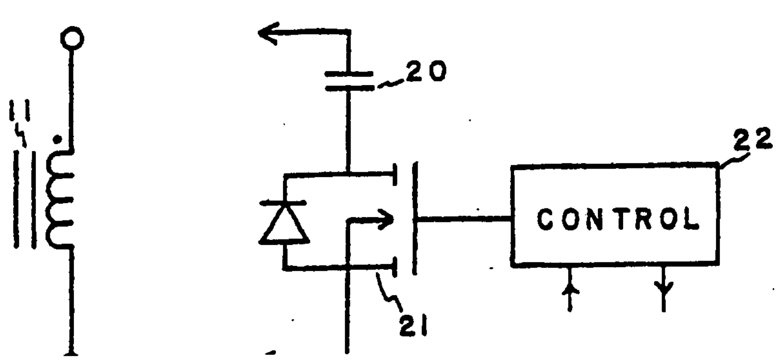

FIG. 4c

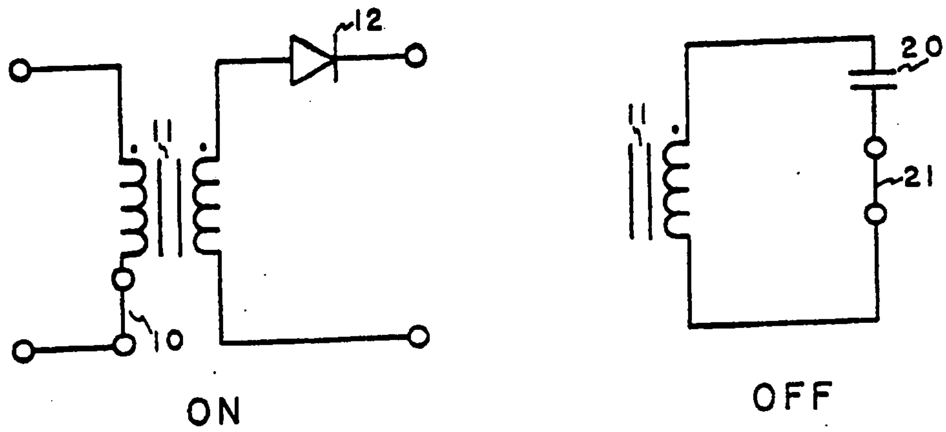

FIG. 4d

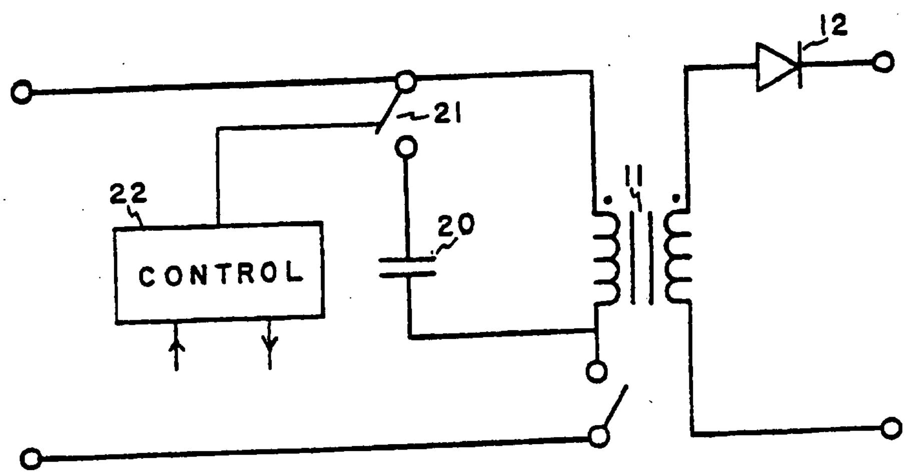

FIG. 4e

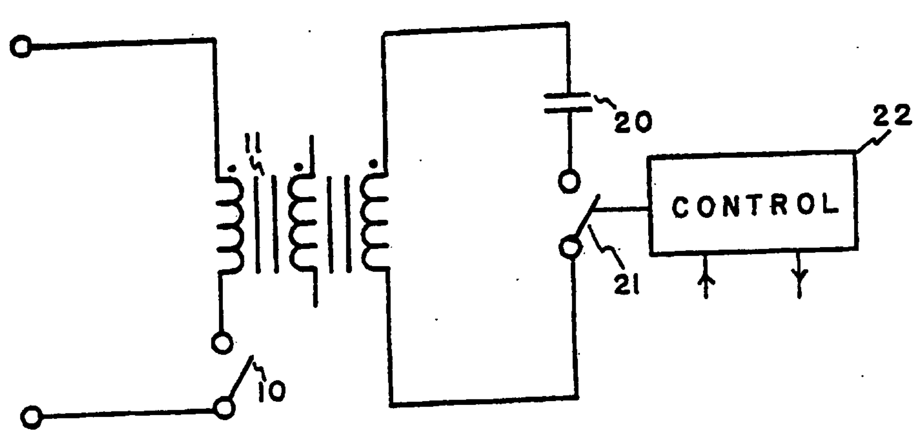

FIG. 4f

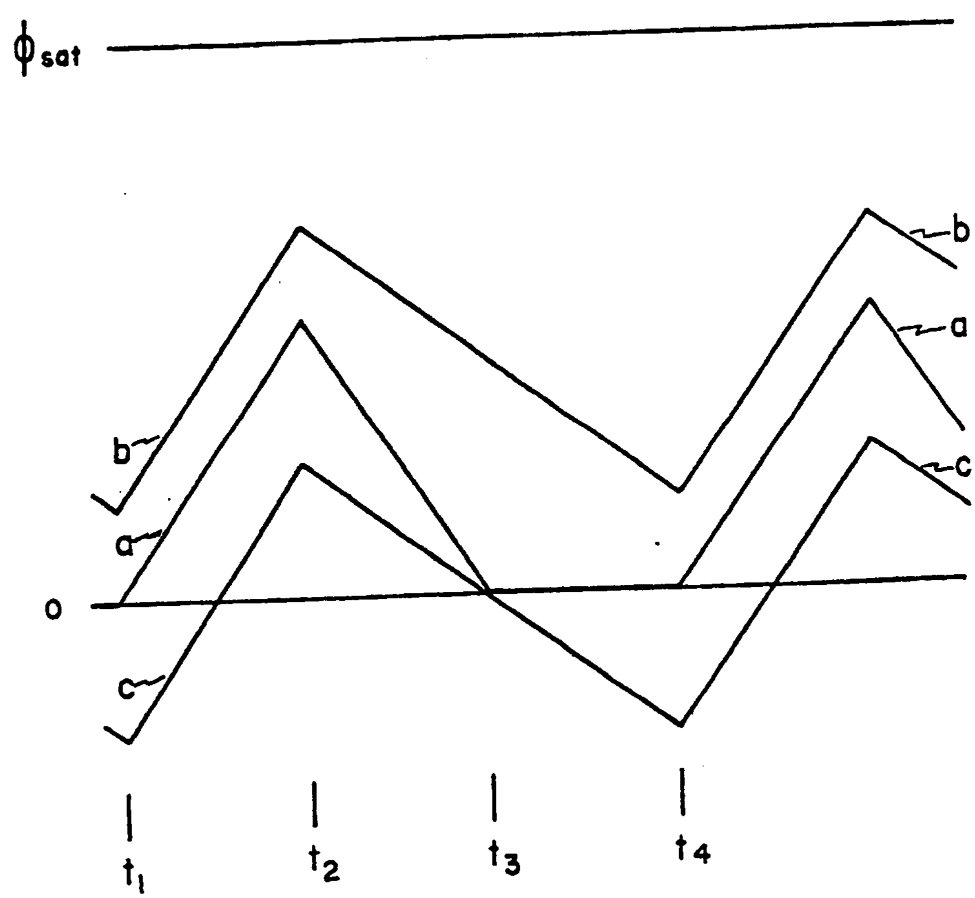

FIG.5

INTERNATIONAL SEARCH REPORT

International Application No PCT/US83/00141

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

INT. CL.[3] H02M 1/18; H02M 3/335
U.S. CL. 363/20, 56

II. FIELDS SEARCHED

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U.S.	363/18-21, 56, 97 307/547-550, 557, 560, 564

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
A	U.S. A, 4,063,306 Published 13 December 1977, PERKINS ET AL.	1-6
A	US, A, 3,963,973 Published 15 June 1976, VERMOLEN.	1-6
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A	S. Hayes, "A Design Technique For Optimizing the Power Device Utilization in Feed-Forward converters", Proceedings of Powercon 8, 1981, pp. 1-10	
A	R. Severns, "Switchmode and Resonant Converter Circuits", International Rectifier Corp.	
A	S. Clemente et al, "A Universal 100KHz Power Supply Using a Single HEXFET", International Rectifier Corp. Application Note AN-939, pp. 60-70.	

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2] 07 April 1983	Date of Mailing of this International Search Report [2] 13 APR 1983
International Searching Authority [1] ISA/US	Signature of Authorized Officer [20] PETER S. WONG